1 Introduction

Underground physics experiments include studies of solar neutrinos, searches for neutrinoless decay, and efforts to detect a new subatomic particle candidate for the dark matter pervading the Universe. These experiments must be built from low-radioactivity components. Existing screening facilities are insufficiently sensitive to meet all the needs of planned experiments, in particular testing for low-energy electron emitters and alpha-decaying isotopes [1, 2, 3]. We propose to meet these needs by constructing a new detector, the BetaCage [4, 5, 6]. The BetaCage will be a low-background, atmospheric-pressure neon drift chamber with unprecedented sensitivity to emitters of low-energy electrons and alpha particles. The BetaCage will provide new infrastructure for rare-event science as well as for a wider community that makes use of radioactive screening for archeology, biology, climatology, environmental science, geology, integrated-circuit quality control, planetary science, and a number of other areas. It will provide an excellent training ground for young scientists in instrumentation for radiation detection and low-background techniques, including undergraduates. The scientists involved will also participate in local public outreach programs.

2 The Need for the BetaCage

Traditionally, experimenters have used high-purity germanium ionization (HPGe) detectors to obtain high-resolution spectra of gamma-ray emission from tens of keV to a few MeV, which enables the identification of contaminants by their characteristic gamma rays. However, HPGe screening may be insufficient for screening contaminants that beta-decay without associated high-energy gamma-ray emission. Mass spectroscopy is sensitive enough to search for some of these isotopes. Nevertheless, of the 79 isotopes listed in Table 1 that decay by beta emission or electron capture, as many as 26 are inaccessible unless screening is employed, or one is able to obtain an extraordinary 1 ppt sensitivity with mass spectrometry. Mass spectroscopy also is destructive and usually requires sample processing that may introduce new contaminants or cloud the relation between the intrinsic contamination level and the measured signal. Low-energy electrons can be detected with thin-dead-layer detectors such as Si(Li) or B-implanted HPGe, but such detectors are available only with small effective areas (at most tens of cm²), have vacuum windows that may stop or scatter some particles, and suffer from backscattering at the detector surface.

A particularly dangerous contamination for a number of underground physics experiments is the deposition of radon daughters from the atmosphere, which decay to the long-lived ²¹⁰Pb, a low-energy beta emitter, and then to the alpha-emitting ²¹⁰Po, with no penetrating radioactivity signature. The beta emitter is the dominant background for the dark matter experiments SuperCDMS [7], EDELWEISS [8, 9], and XMASS [10, 11], and it may dominate the planned experiments GEODM [12, 13] and EURECA [14]. The alpha emitter has dominated the double-beta decay experiment, CUORE [15, 16], and is critical for the large number of dark matter and neutrino experiments that use liquids within containment vessels. Experiments such as CLEAN [17, 18] and DEAP [19] define fiducial regions well away from the container walls in order to reject the short-range alphas, but a sufficiently high rate of alphas will render nonnegligible the probability of misreconstructing such events into the fiducial region. For COUPP [20, 21], movement of the parent nucleus from the surface into the bulk may produce an unrejectable background, and too high a surface alpha event rate would cause significant dead time. Finally, for many experiments (e.g. XENON100 [22], XENON1T [23], LUX [24], LZ [25], DArKSIDE [26], and MAX [27]), (α,n) reactions from surface contamination may be a significant background.

In this case, the ²¹⁰Po alpha emitter is out of equilibrium with the photon-emitting isotopes.

¹Isotopes that decay via electron capture have associated low-energy X-rays and/or Auger electrons, which are emitted in the process of filling the vacancy created by the electron capture.
in its parent $^{238}\text{U}$ decay chain because the uranium parent has been chemically separated. Direct detection of the alpha (or a beta from the nearby parent $^{210}\text{Po}$ or $^{210}\text{Bi}$) is necessary to establish the alpha-emitter contamination level. Screening based on detecting the betas from $^{210}\text{Po}$ or $^{210}\text{Bi}$ has a significantly better sensitivity than the alpha screening if the contamination is due to recent exposure to radon (or to $^{210}\text{Po}$) since it takes significant time for the $^{210}\text{Po}$ daughter to grow in.

The common challenge of detecting low-energy betas and alphas is that the particles cannot penetrate through a vacuum window or through the dead layer of a conventional HPGe detector. Even special purpose detectors with very thin dead layers (e.g., Si(Li), B-implanted HPGe, or silicon surface-barrier detectors) have deficiencies: there remains a vacuum window, there will be backscattering effects that distort the energy spectrum, and it is difficult to obtain the m$^2$ sensitive area desired to obtain high screening throughput and to minimize edge effects. An ideal detector would place the sample directly in the detection medium (e.g. a gas) to eliminate backscattering and dead layer effects while providing a large sensitive area.

### 3 Detector Design

#### 3.1 Overview

The BetaCage, an ultra-low-background drift chamber, is designed around this principle of optimizing detection of $\lesssim 200$ keV electrons and alpha particles from a sample’s surface. Three goals have guided the design from this starting point. First, the detector should use the minimum amount of gas needed to stop particles of interest in order to minimize background from ambient penetrating gammas. Second, the detector should have the minimum possible surface area that itself can be a source of background particles. Third, the detector should provide sufficient spatial information about events to distinguish between those coming from the sample surface and those due to scattering of background particles in the gas.

We choose neon gas at STP based on desired stopping power, feasibility of purification, drift properties (drift speed, diffusion, electron attachment length), and avalanche gain. Neon’s stopping power is large enough that a 30-cm-high drift region will contain greater than 90% of 150-keV betas, so the full spectrum of electrons from likely low-energy emitters such as $^{14}\text{C}$, $^{210}\text{Pb}$, etc., will be contained in the chamber. Likewise, even a 10-MeV alpha particle will be contained in a 20-cm-high drift region. Yet the stopping power is low enough that the trigger MWPC can be thick.
Figure 1: Side view of the BetaCage. The trigger, bulk, and veto MWPCs are indicated, as is the location of the sample. The outer region indicates the gamma shielding.

enough (1 cm) to make assembly straightforward, and the gamma background is sufficiently low in a shield of moderate cost and size. Neon has no long-lived naturally occurring unstable isotopes, so purification by chemical means is sufficient (in contrast to argon).

Figure 1 shows a sketch of the proposed BetaCage. Samples are placed in the gas. An open multi-wire proportional counter (MWPC) directly above the sample provides a trigger for particles emanating from the sample. Above this trigger MWPC is a large region in which the emitted particles stop. The depth and width of the drift region sets the energy of betas whose full energy is contained in the detector. An electric field in this region drifts the ionization to the top of the chamber, where a second open (bulk) MWPC collects it. Proportional avalanching in both MWPCs provides gain. Crossed grids in both MWPCs provide positioning. The time profile of charge collection in the bulk MWPC determines the spatial profile of the track in the z dimension. The trigger MWPC provides a start time to establish absolute z location.

The design minimizes backgrounds due to the chamber itself and provides excellent rejection of residual and unavoidable backgrounds. By design, the only surface of the detector near the sample is that of the wires, whose area is only a few percent of the sample surface area. Events whose tracks do not originate at the sample or do not terminate inside the drift region will be vetoed using the full 3D information. A third veto MWPC below the sample vetoes throughgoing events.

As shown in Table 2, with appropriate construction materials, the limiting background in the BetaCage is ejection of electrons from the sample surface by Compton-scattering photons from contamination external to the detector itself. We will achieve background external photon rates that would result in about 1 keV−1 kg−1 day−1 in a HPGe detector using a 20-cm lead shield surrounding a 1-cm copper liner in the Soudan Underground Laboratory’s DOE-funded Low-Background Counting Facility (LBCF). The LBCF has a 280-square-foot class-10,000 clean room that will provide an active veto shield enclosing the entire 35-m × 40-m × 100-m cavern.

To reduce backgrounds from the detector itself, the chamber and enclosing vessel will be constructed from plastics and copper to minimize gamma emission. Our gas-handling system will pass the neon through cooled charcoal to remove radon and krypton (see e.g. [28, 29]). Radon daughter plate-out onto the wires will be removed by electropolishing [30] prior to stringing the wires in an ultra-low-radon cleanroom [31]. Other background sources, including 14C in the methane quench gas (assuming a conservative ratio of 14C/12C of 10−16 [32, 33]), uranium and thorium in the stain-
<table>
<thead>
<tr>
<th>Source</th>
<th>Rate (keV$^{-1}$cm$^{-2}$day$^{-1}$)</th>
</tr>
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<tbody>
<tr>
<td>Gammas, equivalent to 1 keV$^{-1}$kg$^{-1}$day$^{-1}$ in Ge</td>
<td>3 $10^{-5}$</td>
</tr>
<tr>
<td>5% methane quench gas (assumed with $^{14}$C/$^{12}$C = $10^{-16}$)</td>
<td>5 $10^{-6}$</td>
</tr>
<tr>
<td>Wires: emergent beta rate &lt; 100 keV</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>Wires: rate from gammas in full volume</td>
<td>$10^{-13}$</td>
</tr>
<tr>
<td>30 resistors: Rate from gammas in full volume</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Noryl frames: Rate from gammas in full volume</td>
<td>&lt; $10^{-5}$</td>
</tr>
<tr>
<td>copper field shapers: Rate from gammas in full volume</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>acrylic spacers and vessel: Rate from gammas in full volume</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>stainless steel feedthrough port: Rate from gammas in full volume</td>
<td>$10^{-7}$</td>
</tr>
</tbody>
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Table 2: Expected contributions to beta background levels in the BetaCage.

less steel wire grids, and resistors for the drift-field shaper voltage divider, will be subdominant.

The expected ambient photon background of 1 keV$^{-1}$kg$^{-1}$day$^{-1}$ will yield a Compton-scatter background rate of $3 \times 10^{-5}$ keV$^{-1}$ cm$^{-2}$ day$^{-1}$ ejected electrons. To reach the $10^{-5}$ keV$^{-1}$ cm$^{-2}$ day$^{-1}$ target sensitivity thus requires background subtraction. One day of background measurement would establish a 60 m$^{-2}$ day$^{-1}$ background rate over 0 to 200 keV to a precision of 7.7 m$^{-2}$ day$^{-1}$, allowing detection at almost 3 of a $10^{-5}$ keV$^{-1}$ cm$^{-2}$ day$^{-1}$ rate contaminant in a total of 2 days of running (excluding sample installation and purging of the chamber). Fifteen days counting each for sample and background would allow a sensitivity of $4 \times 10^{-6}$ keV$^{-1}$ cm$^{-2}$ day$^{-1}$ rate.

The BetaCage is an excellent alpha screener thanks to the uniquely short, dense, straight, high-energy tracks resulting from alpha interactions. Gamma rays from natural radioactivity are not high enough in energy to be mistaken for surface alphas. In its underground, shielded environment, unvetoed backgrounds from cosmic rays should be negligible. The dominant background to alpha counting is expected to be from radon daughters in the gas itself that happen to decay in a position and direction that allows their track to mimic one from the sample or that plate out onto the sample itself. The latter is discouraged by the electrostatics; radon daughters tend to be positively charged [34, 35], so they will tend to migrate to the most negative cathode wire (as observed by DRIFT [36]), rather than to the sample. Furthermore, the long-lived daughter worth screening, $^{210}$Po, will have sufficient time to plate out that it never will freely decay in the gas.

The most sensitive commercial alpha detector, the XIA UltraLo-1800 [37], also a gas chamber (using Ar), has demonstrated backgrounds as low as $2 \times 10^{-3}$ cm$^{-2}$ day$^{-1}$ with a 1800 cm$^{2}$ sample area. With the BetaCage’s design advantages (cleaner gas, lower surface area of material in the fiducial region, tracking, shielded operation underground, etc.), we expect an alpha background $\gtrsim 100 \times$ lower. For two weeks counting, the expected sensitivity $\sim 0.1$ counts m$^{-2}$ day$^{-1}$.

### 3.2 Detailed Technical Design

Each MWPC in the BetaCage consists of 3 planes of wires: a central anode plane and two cathode planes. The electrostatic design of the MWPC unit cell is illustrated in Figure 2. The voltages on the MWPC grids set the gain via the Diethorn formula

$$\ln G = \ln \frac{2}{V} \ln \frac{2}{v_0 E_{\min} \rho_0}$$

where $G$ is the gain, $V$ 41 V (90%/10% Ne/CH$_4$) is the potential difference through which an electron must be accelerated to ionize a gas molecule, $v_0$ is line charge density for a given voltage, $r_0$ is the wire radius, $E_{\min}$ 10 kV/cm (90%/10% Ne/CH$_4$) is the electric field needed to start an avalanche, $\rho$ is the gas density, $\rho_0$ is the gas density at STP, and $\epsilon_0$ is the permittivity of free space.
Figure 2: BetaCage electrostatic design. Left: MWPC gain as a function of trigger MWPC anode voltage (cathode set to 0 V) and bulk MWPC anode voltage (cathode set to 2100 V). Right: Equipotential surfaces for a single MWPC cell. The anode wire runs down the center and the cathode wires are at top and bottom. The scales along the axes indicate distance in µm. The voltages are indicated at right.

space (see, e.g., [35]). ∆V and $E_{\text{min}}$ are calculated using GARFIELD$^2$. Gains of approximately $10^4$ for the bulk MWPC and $10^5$ for the trigger MWPC are sufficient to overcome electronics noise. Fortunately, the exponential dependence of gain on voltage (via $\lambda$) makes both gains achievable with modest voltage differences of roughly 1100 to 1300 V, as shown in Fig. 2. Because our calculations do not take into account the Penning effect, the gains obtained in practice will be larger. Gain is easily calibrated in situ using 6 keV X-rays, as shown in Figure 3.

The desired gains are achieved with wire spacing of 5 mm (in-plane and between planes), which yields a reasonable total wire count for the structure (∼ 200 per grid) while also providing fine enough position resolution that track diffusion rather than wire spacing is limiting. The anode wires are 25 µm and the cathode wires 125 µm in diameter.

Because contamination by $^{14}$C in the quench gas is a consideration, we will experiment with use of a CH$_4$ fraction of 5%. The drift field is determined by requiring that ionization track diffusion over the drift distance is small compared to the 5-mm wire spacing (so the wire density is not excessive). The expected drift velocities are 1.7 cm/$\mu$s (1.6 cm/$\mu$s) for 90%/10% (95%/5%) Ne/CH$_4$, while the corresponding diffusion at 50 V/cm is expected to be 471 µm/$\sqrt{\text{cm}}$ (498 µm/$\sqrt{\text{cm}}$). For the 40-cm-drift region, we expect 3–4 mm of diffusion.

3.3 Gas Handling

To ensure low backgrounds, it is especially important to limit the radon in the chamber. Radon may be emanated by materials and is present in the commercial Ne/CH$_4$ mix (formed from ultrahigh purity neon and chemically pure methane) at small levels. To remove this radon, the gas-handling system includes a standard cooled, carbon radon trap (see e.g. [39]). While such a trap is fundamentally simple, care must be taken that the carbon itself has low radon emanation. Furthermore, the packing of the carbon must be as tight as possible to minimize channels through which radon may pass without adsorbing to the carbon. We have acquired a suitable synthetic carbon, CARBOXEN. This trap will also be effective at removing $^{85}$Kr, a lesser background.

The cost of neon gas makes it cost-effective to recirculate the Ne/CH$_4$ mixture. We will use a KNF Neuberger NP015 1 liter-per-minute pump. A SAES Pure Gas PS11-MC1-CH getter-stabilized zeolite gas purifier will remove water, CO$_2$, O$_2$, non-methane hydrocarbons, and particulates greater than 0.003 µm in size from the exhausted gas. The Ne/CH$_4$ mixture fraction should remain essentially constant for the days to weeks of counting between gas replacement since the event rate in the chamber will be low enough that dissociation of the methane is negligible.

http://garfield.web.cern.ch/garfield/
3.4 MWPC Design

The driving concerns for the MWPC design are gain stability, gain uniformity, and radiopurity. It is the most challenging aspect of the detector.

Gain stability and uniformity is required so that the energy resolution of the design, set by ionization creation statistics and readout noise, is not degraded by variation of gain with position across the MWPC or with time. Considering fluctuations in Equation 1, we find that 5% variation in gain arises from 2.5 V (0.2%) variation in voltage, 1.5% variation in anode wire diameter, or 100 µm (2%) variation in wire spacing. While voltage stability is easily achieved with commercial units, the constraints on machining, assembly precision, and stability are stringent. Tensioned wires are necessary, where 20-g and 200-g tensions for the anode and cathode wires, respectively, limit sag under gravitational and electrostatic forces to less than 30 µm, yielding <1% gain variations.

The radiopurity challenge leads us away from standard MWPC construction materials like G-10 and metals in favor of plastics. Noryl is acceptable: screening with the UMN Gopher HPGe detector demonstrates contamination levels of no worse than about 5 mBq/kg $^{238}$U, $^{232}$Th, and 30 mBq/kg $^{40}$K, quite acceptable, yet Noryl is also strong enough to handle the tension (40 kg in each direction for the cathode wires for the full BetaCage) and can be precision machined if properly annealed. The field shapers can be made of acrylic, which is also known to be quite clean.

The final design employs a Noryl frame manufactured as four arms that are then bolted together. An assembled frame is visible in Figure 3. The holes for the wire feedthroughs are centered with 10 µm precision, and the dimensions of the pieces meet tolerances of 125 µm. Two arms have holes for the anode wires, while the other two arms have holes for the crossed cathode plane wires.

The holes accept brass feedthroughs modeled on those developed for the BaBar wire chambers, shown in Figure 3. The cylindrical outer dimension press fits into the holes in the Noryl, and they have a 100 µm hole (175 µm for the cathode wires) that centers the wire. A copper tube inserted into the other end of the brass pieces guides the wire into the feedthrough and is crimped to keep the wire in place. The wires are crimped into the feedthroughs under tension. Springs in the feedthroughs at one end of the wires are compressed in this process, maintaining tension in case the wires relax and also providing some compliance in case the wires are disturbed.

4 Results from Prior Support

DUSEL R&D grant NSF/PHY-0834453 (PI: Schnee, Co-PI: Golwala, $200,841, 6/1/2007-5/31/2012) along with Schnee’s startup and Golwala’s DOE companion grant DE-FG02-07ER41481 ($172,000, 7/15/2007-7/14/2011) and base funding, has supported the work leading to the design described above. In particular, this grant has supported the construction and testing of a half-size prototype, with drift volume of 41 cm × 41 cm × 22 cm. As described below, these tests have demonstrated the detector design. Doubling the size of the detector should pose no major challenges. We expect to demonstrate full track reconstruction by start of funding of the proposed work, which will fully validate the design of the full BetaCage aside from scaling to larger size and background levels in situ.

At Syracuse, the grant partially supported three graduate students (for a total of three semesters full-time) and one post-doctoral researcher, as well as three undergraduate students. One graduate student, Manungu Kiveni, wrote and commissioned data-acquisition software and led an undergraduate, Thomas Goldstein, in testing of the noise performance of the high-voltage filtering and data-acquisition system. Mr. Kiveni will be graduating this summer (primarily based on CDMS work) and has accepted a postdoctoral position at Fermilab. The other two graduate students, Jason Wiggins and Boqian Wang, set up and performed Monte Carlo simulations of the detector to aid in detector design, materials choice, and track reconstruction. The Syracuse post-doctoral
A wire passes through the hole in the center of the left brass part, through the right brass part and into the copper tube, where it is crimped.

researcher, Dr. Marek Kos, was supported for 24% of his time from September 2010–May 2011. He worked on low-background counting and the design of the gas-handling system and wire connectors, leading two undergraduates, Deng Chao and David Tagg, in prototype machining, design tests, and calculations. A fourth undergraduate, James White, performed calculations and measurements related to the electropolishing of stainless steel wires as an independent study course.

At Caltech, Golwala’s DOE companion grant and base funding partially supported graduate student Zeeshan Ahmed, postdoc Bob Nelson (ongoing), and four undergraduates. Ahmed received his Ph. D. in 2011 based on his design work for the BetaCage (and the analysis of CDMS II data). Nelson has been on the project since August, 2010, taking over design and assembly work from Ahmed. He has managed the demonstration of the $^{55}$Fe testing of the MWPC design, supervising four undergraduates: Dan Sotolongo, who helped develop the stringing technique, strung the rst MWPC and its prototype, and also developed the LABVIEW data-acquisition; Sinthunon Chavanaves, who worked on GARFIELD simulations; Alex Rider, who worked on printed-circuit board design, wiring, acquired and analyzed the data sets presented in Section 4.1 and Alex Zahn, who is developing runtime software and firmware for readout. Both Alex Rider and Alex Zahn have been granted Caltech Summer Undergraduate Research Fellowships for summer, 2012, and will work under Dr. Nelson’s supervision to do the tests described below towards demonstration of full track reconstruction for electrons. This work has resulted in one publication [6].

The Caltech group has been involved in the Caltech Classroom Connection, doing educational outreach with high school students in the Pasadena area. The group visits high school physics classes for a day once every two to four weeks, presenting a demonstration related to their curriculum and assisting with laboratory exercises. In addition to enriching the existing curriculum, these visits serve to encourage students to consider careers in science and technology.

4.1 MWPC Assembly and Performance

A clever assembly jig, shown in Figure 3, enables the stringing of a single wire in 6 minutes with good control of positioning, feedthrough insertion force, and tension. A full MWPC for the prototype, with 237 wires, was assembled in 5 days by 3 people in December, 2011. The two MWPCs for the prototype BetaCage are fully assembled.

We have tested these MWPCs by exposing them to a $^{55}$Fe X-ray source, with lines at 5.89 (Mn K$_\alpha$) and 6.49 (Mn K$_\beta$) keV. The anode wires were read out using a Cremat CR-111 two-stage charge-integrating amplifier with 0.13 V/pC gain, 150 $\mu$s decay time, and 3 ns intrinsic rise time. The output was digitized with a 60 MHz, 12-bit National Instruments PCI-5105 ADC.

The performance is excellent, as indicated by the spectrum shown in Figure 4 obtained after
tuning the anode voltage to 2100 V to ensure good separation of the X-ray events from noise while avoiding saturation. The $^{55}$Fe peak is readily visible, as is the argon K-shell escape peak (3 keV). Assuming the standard value of 26 eV deposited energy per electron-ion pair, we reconstruct that the MWPC gain is $2 \times 10^5$. The energy resolution at 6 keV is 18% estimated from a double-Gaussian fit to the two K-shell peaks, where the theoretical estimate is 12.8% based on Fano statistics. The electronics noise contribution is only 0.8 mV relative to a peak height of 100 mV at 6 keV. The excess width may be due to position dependence of the gain, which cannot be corrected for with this simple readout. We measured that the gain depends on gas pressure as $G = 67\delta\rho/\rho$, consistent with expectations within the theoretical uncertainties. The peak mean drifts by no more than 1% over 24 hours, and there is no measurable change in width either, indicating gas aging (purity) and space-charge effects are negligible compared to counting statistics. A publication on the MWPC design and demonstration is in preparation for submission during summer, 2012.

4.2 Full Readout System

A full readout system must be more capable than the charge-integrating amplifier used above because of position dependence in the signal, as perhaps already seen in the above test. An electrical model reveals that the pulse shape depends on the position of an event along a particular wire at the 30% level (Figure 5). Since energy resolution is important for the BetaCage, it is necessary to recover as much information about the pulse shape as possible to correct for these variations and reach the resolution limit imposed by counting statistics. This requires digitization at speeds approaching 1 GHz as well as full readout of the crossed cathode, which also provides position information. The open-source ROACH platform\(^3\) provides a low-cost way to do so.

It is not cost-effective to read out each wire individually. In the veto and trigger MWPCs, we gang all the wires together since we do not need to reconstruct position there. We gang the edge wires of the bulk MWPC anode and cathode together to form veto regions, and we gang the remaining bulk wires together in a pseudo-random fashion. This latter ganging is chosen so that it is always possible to reconstruct which cells were hit by combining pulse shape information with the crossed-wire hit information. For the full BetaCage, we can divide the anode and cathode into 16 20 gangs of 8 10 wires per gang with 42 readout channels.

The readout system thus developed is as follows. At the vacuum feedthroughs to the chamber, we place front-end wideband voltage amplifiers consisting of two stages of the Mini-Circuits PSA-5454+ 50 MHz to 4 GHz low-noise MMIC amplifier followed by a 500-MHz cut-off anti-alias iter. These boards receive the high voltage from a commercial unit whose output has been low-pass

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\(^3\)from the Center for Astronomical Signal Processing and Electronics Research, \url{http://casper.berkeley.edu}
Figure 5: Left: Electrical model for BetaCage MWPC pulse shape. The avalanche event at a particular point along the wire acts as a current source $I_s$ injecting current into the anode (sense) wire. That wire is treated as a transmission line formed by the anode wire and the nearby anode and cathode wires (characteristic impedance $Z_w$ given by the capacitance to adjacent wires and the wire inductance and resistance). It is unterminated at one end and connects to a coaxial cable (impedance $Z_c$) and then to an amplifier (not shown) with input impedance $Z_{out}$ at the other. The anode wires ganged together with this one appear as a shunt impedance to ground. Right: Dependence of pulse height and shape on position in steps of 10% of the wire length for a 1-m wire. The small dot-dashed line is the input current pulse. The increase in pulse height is due to the gain of the amplifier, which is included in the model because its bandwidth affects the pulse shape. The 30% variation in peak height is due to the resistance of the anode wire, while the variation in pulse shape arises from the dependence of the effective $R$ and $C$ on the position of the event along the wire.

Figure 6: Energy resolution plotted against the number of hits for a 150-keV electron. The ADC quantization noise is the dominant contribution, about 0.2 keV. The ADC full scale of 2 V corresponds to roughly 200 keV energy deposition. The amplifier performance is shown in Figure 6.

4.3 Work Toward Full Track Reconstruction and Efficiency Determination

We have done simulations to gauge the ability to reconstruct tracks given the wire ganging scheme used above. We took tracks created in GEANT4, assigned the charge to MWPC cells of size 5 mm, combined signals from ganged wires, and added electronics noise. For each wire hit, the algorithm makes a list of unit cells the hit could be assigned to given the anode and cathode wires and timing. It then takes the hit closest to the sample and sees which of its nearest-neighbor candidates has a hit. It then tries to find adjacent hits for those secondary hits found, and the process is repeated until a full track is reconstructed. In the absence of noise, the algorithm works perfectly given the wire gangings discussed above for the full BetaCage. When one adds noise, uncertainties in the $z$ coordinate of each wire hit may cause ambiguities for tracks with many wires hit about the same
Figure 6: Left: Expected energy resolution as a function of input energy. The dashed-dotted line is the statistical fluctuations in number of charge pairs created, the dashed line is the noise of the analog component of the readout (thermal and amplifier noise), the dotted line is the digitization noise, and the solid line is the quadrature sum. Note that the statistical noise does not degrade the determination of pulse shape and position; it only comes in when converting from pulse height to energy. Right: Test of front-end amplifier. An input pulse with 1.2 ns rise time yields an output pulse with 1.6 ns rise time and gain of 100.

Figure 7: Left: Efficiency for containment of events in the BetaCage. An event originating in the sample under the fiducial section of the trigger grid can be lost if it enters the veto region, or if the electron suffers a large deflection and returns to the sample, depositing less than its full energy in the drift region. Shown is the fraction of events fully contained in fiducial region as a function of energy for the full BetaCage (solid) and the prototype running neon (dashed), for a source at the center (red) or 20 cm from the center (blue) of the fiducial region. Right: Image of an originally 65-micron-diameter stainless steel wire after 2 minutes of electropolishing, which reduced the diameter about 9 microns.

z coordinate. However, as noted above, the electronics-limited signal-to-noise for a single cell is already roughly 10, and it is possible to increase the MWPC gain and/or amplifier gain easily if this is insufficient, so it should always be possible to run in a mode minimizing losses.

We have also simulated the efficiency for full containment of a track in the fiducial region for the prototype and full BetaCage, as shown in Figure 7. The full size BetaCage loses efficiency above 100 keV as one moves out from the center of the fiducial region, but remains acceptable. The larger efficiency loss is from electrons that terminate back on the sample before losing their full energy. These will be easily identified via the track image.

5 Plans for the Prototype BetaCage

Machining of the final parts for the prototype BetaCage should be finished in May, 2012. The amplifier design is being revised now and should be delivered by June, 2012. The ADC/ROACH
readout is completely in hand, so the effort consists of writing the firmware and software needed to use it. It is reasonable to expect that all these parts will be in place by the end of June, 2012.

The next step will be to fully understand the properties of the gases we will use. With the prototype BetaCage, we will be able to calibrate on and verify for P10 the known Diethorn parameters \( E_{\text{min}}(\rho_0) = 48 \pm 3 \text{ kV/cm} \) and \( V = 23.6 \pm 5.4 \text{ V} \), the electron drift speed, and electron diffusion. The gas gain and diffusion measurements will be made by varying the anode voltage and the pressure while measuring the signal from a mono-energetic particle with point-like energy deposition (e.g. \( ^{55}\text{Fe} \) X-rays). To measure drift speed, alpha particles are appropriate because they deposit energy both in the trigger MWPC (yielding a start time) and the drift region but have have short and simple tracks. Once we fully understand the gas properties, we will use a \(^{109}\text{Cd} \) electron source to create extended tracks in the drift volume.

We will repeat these tests and measurements with Ne/CH\(_4\) mixtures after the gas handling system is delivered, in summer 2012. During fall, 2012, we will measure the above-ground background for alpha-screening measurements. As explained in Section 3, it should be quite low, even in the above-ground environment and without radon-abated assembly.

6 Plan of Work

Our schedule and plan of work is given below, with dates specified relative to an assumed October, 2012, funding start date. We note that the personnel on this project will be working part of their time on a dark matter detection experiment. This splitting of time may result in interferences between work needed on the dark matter experiment and this project that limit the rate of progress on critical path tasks. We have accounted for such possibilities in the work schedule.

Prior to funding, we will scale the design of the MWPC for the prototype BetaCage to the full BetaCage and manufacture one frame so that it can be strung as a test of the modified design. This process will test the modifications of the wiring jigs made for the full BetaCage and fully transfer the stringing techniques to Syracuse. (Dr. Bunker and Mr. Wang participated in the December, 2011, stringing of the second prototype BetaCage MWPC, see Section 4.1.)

We will also test the electronics for the full BetaCage with the prototype BetaCage at Caltech; these electronics are due to be received in June, 2012.

6.1 Year 1

The new Syracuse graduate student, Michael Bowles, performed Monte Carlo simulations to set the width of the veto region, supported last summer by other funds. Throughout Years 1 and 2, Mr. Bowles will extend his and Mr. Wang’s simulation work on for the BetaCage, with the aims of understanding detector inefficiencies and backgrounds and informing data analysis efforts. He will simulate the expected backgrounds from all anticipated sources to determine the expected rates of events in the bulk volume alone as well as those with tracks in the trigger region, both with and without samples present. The measurement of the rate in the bulk volume will determine the photon background flux, and hence allow subtraction of the inferred rate of events in the trigger region. Analysis of the expected rates also in the veto regions of the BetaCage may allow the statistical subtraction of vetoed events, improving sensitivity to high-energy betas. Simulations of betas from samples will determine the expected spectrum for various contaminants as functions of energy and position and will inform the writing of reconstruction algorithms to determine the head/tail of tracks, reducing backgrounds from electrons that start in the bulk gas volume and end on the sample. Simulation of the full spectrum expected from the complex decay chain of \(^{210}\text{Pb} \) will inform the screening for this most important beta-emitter.

In the first quarter of Year 1, we will work with engineers (likely at FNAL) to design the gas vessel to contain the BetaCage. Our preliminary design is that the vessel will be made mostly
of acrylic to minimize radioactive contamination; a narrow leg (likely low-radioactivity stainless steel) will extend out from the vessel with the needed SHV feedthroughs. There will be additional ports for the gas flow and a load-lock mechanism for inserting a sample tray without exposing the detector to radon from the mine air. This chamber need not be a pressure vessel (which would be prohibitively expensive). Since we will not recover the neon mix from the chamber at the end of each run, it will be unnecessary to bring the chamber volume down to vacuum. Included in this work will be the design of a wire harness scheme to carry all the signals to the SHV feedthroughs.

Also in the first quarter of Year 1, the Syracuse machine shop, using a design based closely on the successful prototype BetaCage, will fabricate the Noryl MWPC frames, copper and acrylic electric-field shapers, and brass feedthroughs. Dr. Bunker will supervise the Syracuse undergraduate in cleaning and storing these components; machining oils and other debris will be removed via ultrasonic cleaning and rinsing with isopropanol and ultra-pure water, and a radon-purge cabinet (already constructed) will house components until needed during assembly in the subsequent quarter. Dr. Bunker will also lead the undergraduate in the removal of radon daughters from the outer micron of the stainless-steel anode and cathode wires via electropolishing with a partially automated setup to be completed by the Syracuse group this summer using start-up funds. We have already demonstrated the ability to remove a consistent thickness of stainless steel wire using our electropolishing set-up, confirmed by images with a scanning electron microscope (see Fig. 7).

In anticipation of installing the shielded detector, we will pay for the engineering study and floor reinforcement to allow the 14-ton shielding to be installed in the Soudan LBCF. Similar work done for a HPGe station there indicates the total cost will be about $5,000.

During this design and construction work, Dr. Nelson will lead the graduate students on tests of the prototype BetaCage using neon gas, as described in Section 5.

In the second quarter of Year 1, Drs. Bunker and Nelson will lead Mr. Bowles and the Syracuse undergraduate in the stringing of the full BetaCage inside the Syracuse low-radon cleanroom. Syracuse start-up funds have already been used to purchase a larger optical bench, rails, and precision-alignment bar to accommodate the larger size of the BetaCage Noryl frames. Based on the prototype, we expect the BetaCage stringing to take six weeks of full-time effort from a rotating team of three people, typically consisting of one post-doc, one graduate student, and one undergraduate, with Caltech personnel traveling to Syracuse for shifts on the task. Radon levels and general cleanliness will be monitored throughout the assembly with an electrostatic alpha counter and standard particle counter, respectively (also purchased with Syracuse startup funds). Each completed MWPC will be stored in the nitrogen-purged radon-free cabinet until final assembly.

In parallel, the Syracuse shop will machine and assemble the acrylic vessel. We will fill the vessel with low-radon liquid-nitrogen boil-off, and Mr. Bowles will lead leak-testing of the vessel.

In the third quarter of Year 1, Dr. Bunker will lead Mr. Bowles and the Syracuse undergraduate in the construction of the full detector in the acrylic vessel and the resealing of the vessel at Syracuse. The Caltech graduate student will work on the data pipeline and reconstruction software.

By the end of the third quarter of Year 1, Dr. Bunker will work with Syracuse machinists to specify the shield design and purchase the OFHC copper, 14 tonnes of low-radioactivity lead, and other materials needed to realize a gamma-ray shield with no line-of-sight from the outside to the inner, shielded volume. The shield will include structural supports, an opening mechanism for accessing the acrylic vessel's load-lock mechanism, and a gas-tight radon-purge volume. The machining of these parts will occur in the fourth quarter of Year 1.

In the fourth quarter of Year 1, we will perform the first tests of clean cage in the acrylic vessel at Syracuse. We will verify the gas parameters for P10 and for neon mixtures measured with the prototype. The larger drift region of 40 cm will enable us to measure the electron drift velocity and diffusion on a longer length scales than in the prototype.
6.2 Year 2

In the first quarter of Year 2, we expect all components of the shield to have been delivered to Syracuse, and all remaining machining for the shield will be completed. Additionally, Dr. Nelson will lead a Caltech student (perhaps an undergraduate working for course credit) in integrating trigger signals from the LCBF muon veto with the ROACH-based data-acquisition system.

In the second quarter of Year 2, Dr. Bunker will lead Mr. Bowles and the Syracuse undergraduate in the assembly of the shield, taking advantage of his experience with the clean assembly of the CDMS II lead and polyethylene shields while a graduate student at UCSB. A temporary class 10000 clean room will be set up in the sub-basement of the Syracuse physics building. Within this enclosure, clean-room protocol—full Tyvek suits, hair nets, latex gloves and face masks—will be followed in order to maintain the cleanliness of the materials as well as the safety of the participants. Each fabricated component and lead brick will be cleaned with isopropanol and dried according to the shield design. After testing the shield’s opening mechanism and measuring the performance of the radon purge (with either a Rad7 or a custom-made electrostatic alpha counter), the shield will be disassembled, clearly labeling and documenting each component and lead brick to allow exact reassembly. Finally, each piece will be cleaned a second time with isopropanol, wrapped in thick plastic, packaged into wooden crates, and shipped to the Soudan Mine. Based on previous experience, this entire process should take about twelve weeks.

In the third quarter of Year 2, Dr. Bunker will lead the unpacking and assembly of the shield at Soudan’s LBCF. With support from the mine crew, we expect the reassembly of the shield to take 2 weeks. Syracuse will pack and ship the acrylic vessel to Soudan for assembly within the shield. Dr. Bunker will lead Mr. Bowles in the reassembly and leak testing of the gas-handling system and empty vessel within the LBCF. Concurrent with this work, the MWPC frames will be sealed in desiccated argon-overpressured pressure vessels. These vessels will be packaged in shock-absorbing crates for transport. To enable transfer underground, the crates will be designed to fit within the hoist cages at the Soudan Mine. Our experience with transportation of the CDMS dark-matter detectors leads us to choose to drive the MWPC frames from Syracuse to Soudan rather than use a transportation company. The field-shapers and sample tray will be similarly packaged and transported. Each shipping container will be monitored for acceleration and temperature with automated data loggers, permitting forensic diagnostics in the unlikely event of damage during transport.

In the fourth quarter of Year 2, Drs. Bunker and Nelson will lead the assembly of the BetaCage at Soudan’s LBCF. With rotating 2-week shifts of the Syracuse and Caltech students, we expect to complete this work before the end of the (summer) quarter, permitting time for a suite of system tests prior to commissioning. The field-shapers, MWPCs and sample tray will each be carefully unpacked, inspected for damage, and cleaned with isopropanol. The BetaCage will be assembled and then transferred to the interior of the acrylic vessel, all while obeying strict clean-room protocol and using old-air purge to limit radon plateout onto the wires. Before nally sealing the vessel, the MWPCs will be connected to the high-voltage feedthroughs via low-radioactivity Kapton-insulated coaxial cabling and electrical continuity checks will be performed. The full complement of high-voltage biasing and readout electronics will be unpacked, installed, and connected to the external sides of the feedthroughs. With the shield still open, a nal round of leak testing will be conducted, the radon levels will be measured with a conventional Rad7 alpha counter prior and subsequent to establishing the shield’s radon purge, and the gas-handling system will be used to repeatedly flush the acrylic vessel with low-radon liquid-nitrogen boil-off gas. Additionally, the MWPCs will be biased with a few kilovolts to check for arcing. Finally, the shield door will be attached, and the acrylic vessel’s load-lock mechanism will be reassembled and tested.
In the first quarter of Year 3, the BetaCage will be fully commissioned in the Soudan LBCF. Drs. Bunker and Nelson will lead rotating teams in establishing stable running conditions and characterizing the performance of the detector in situ. Neon-gas circulation will be initiated, and the on-site mine crew will be trained in how to monitor and exchange neon-gas bottles and liquid-nitrogen dewars without interrupting detector operation. To begin, short test runs will be used in conjunction with low-energy gamma-ray sources to re-establish the detector functionality (e.g., drift properties, gain and energy resolution), comparing to prior measurements (made at Syracuse). The data-acquisition software and a data pipeline will be tested as well, enabling on-site monitoring, experimental control, and availability of data for post-run analysis. Once nominal operating parameters have been determined, the first extended runs will be performed with and without the sample tray, and with a radio-pure sample (e.g., a bare Si wafer) in order to measure background levels. These first ultra-low-background data will be used to determine the background gamma flux in the detector and to benchmark the Monte Carlo simulation described above, thereby refining our understanding of the detector’s ultimate sensitivity and allowing robust subtractions of background.

In the remainder of Year 3, the fully commissioned BetaCage will be used to screen high-priority samples from the many interested underground physics collaborations mentioned in Section 2 (see also letters of collaboration). In the beginning of this operational phase, Drs. Bunker and Nelson and the graduate students will rotate in traveling to the Soudan Mine to operate the detector and supervise screening runs, while gradually training Soudan’s mine crew in the proper procedure for changing samples via the load-lock mechanism. Eventually, we envision entirely remote operations, with a sample queue maintained by the LBCF’s on-site technical staff. Once commissioned, the operating cost will be minimal: monthly electrical and network service, replenishment of neon gas, pump and filter servicing, spare electronics modules, and by-the-hour labor costs for work done by the mine crew. Furthermore, we will need a mechanism to charge users in order to pay for these maintenance costs.

7 Broader Impacts

Broader impacts of this work include 1) the creation of screening infrastructure of use both to the rare-event search community and to other scientific fields, many of great general societal interest; 2) training of scientists in radiation-detection technologies and low-background techniques, which supplements the country’s technical intelligence base both inside and outside physics; and 3) public outreach to grade school and high school students to supplement and improve local physics
education. We describe each of these impacts in more detail below.

7.1 Screening Infrastructure

As described in Section 2, construction of the BetaCage will enhance the infrastructure for underground physics by providing unique and important materials screening for rare-event searches. The BetaCage can also provide more sensitive and/or less expensive isotope dating for other fields, especially with $^{14}$C and tritium. The carbon or hydrogen source would be converted to CH$_4$ and used as the quench gas, in a 90% neon, 10% CH$_4$ mix. For the background level expected here, a sensitivity to $^{14}$C/$^{12}$C $\approx 10^{-16}$ is expected, comparable to accelerator mass spectrometry and less expensive. Moreover, the BetaCage could reach levels of $^3$H/$^2$H of $3 \times 10^{-19}$ in a single day's counting, greatly improving the available sensitivity. Such sensitivity is of interest to pollution control agencies: the amount of tritium provides information about general water quality because it measures downward migration of contaminants. Additional dating can be done with beta-emitting isotopes such as $^{210}$Pb, used for dating sediment and organisms such as coral, and with very long-lived isotopes $^{10}$Be and $^{36}$Cl (cosmic-ray spallation products), which are used to study geology, hydrology, climate, and planetary physics by extending dating to ancient times.

Ultra-sensitive beta counting is also useful in fields that use beta radioisotopes as tracers, such as medical applications where the amount of radiotracer injected must be kept to the minimum. Geomicrobiologists use radioactive tracers such as $^{35}$SO$_4$ or $^{14}$CH$_4$. Detecting ever smaller amounts of these tracers in environmental water or rock samples enables researchers to detect and quantify the extremely low, in situ, subsurface microbial respiration rates.

Finally, better alpha screening is important for the Si-chip industry. Integrated circuits can suffer single-event upsets due to alpha emission from $^{210}$Po, which appears as a decay product of $^{210}$Pb in lead-based solders and as a radon daughter (see e.g. [41]). In order to maintain reliability at ever increasing circuit density, the alpha rate must be kept below 50 alphas m$^{-2}$ day$^{-1}$, which is beyond the means of the industry standard technology but orders of magnitude higher than the expected BetaCage sensitivity.

7.2 Student and Postdoc Education

The broad range of training that students and research associates receive while carrying out this effort will serve them well in their future careers, whether they continue to work in underground physics or apply their expertise in other areas of national need. Direct applications include the development of radiation detectors for use in nuclear energy or national security, medical physics, medical imaging, and manufacturing quality control. Our students will also receive general training in mechanical and electromagnetic design, precision construction, gas handling and purification, electronics, computer programming, and data analysis. These kinds of technical expertise are applicable in a wide variety of scientific fields. The results of our prior support on student and postdoc education is discussed in Section 4. We will continue to involve undergraduates in work for course credit and via summer research fellowships.

7.3 Public Outreach

The Soudan Lab has a broad impact on the general public via daily science tours for summer tourists and for school groups during the academic year. We will take advantage of our siting the screener at Soudan’s Low-Background Counting Facility by contributing to this public outreach. Dr. Nelson and the Caltech graduate student will also continue local outreach work with the Caltech Classroom Connection.
References


